Effect of ambient on the thermal parameters of micromachined bolometer

K. S. Nagapriya*, A. K. Raychaudhuri†

Department of Physics, Indian Institute of Science, Bangalore 560 012, India.

V. K. Jain, C. R. Jalwania and Vikram Kumar

Solid State Physics Laboratory, Lucknow Road, New Delhi 100054, India

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The thermal characterization of bolometers is needed for optimal design as well as applications. In this paper, we present results of the effect of environment on the thermal properties of micromachined bolometers. We find that while in vacuum the thermal response can be represented by a single time constant, in presence of an ambient gas the thermal reponse can no longer be described by a single time constant. This will have a direct implication on frequency dependence of responsivity. We present a model to explain our data which involves the finite diffusion time in the ambient gas and the associated extra thermal mass.

Microbolometer arrays fabricated using Micro-Electro-Mechanical Systems (MEMS) technique [1] are used for thermal image processing. Thermal response characterization of microbolometers is needed for optimal design. Generally thermal characteristics are quantified through two measureable quantities - the thermal resistance of the bolometer to the substrate R_{th} and the thermal relaxation time τ. The thermal parameters are measured at a single bias voltage across the bolometer and also as a function of applied bias across the bolometer [2, 3]. Application of excess bias leads to heating of the bolometer. This provides thermal characteristics at elevated temperatures. In this report we address the specific issue of ambient. The ambient gas provides an additional thermal link of the bolometer to the substrate in addition to the support hinge and reduces R_{th}. This changes the responsivity of the bolometer which is $\propto R_{th}$. By measuring the thermal characteristics in vacuum, air and Helium gas ambient we have shown that the ambience not only changes the thermal link resistance R_{th}, but more importantly, changes the nature of the time-temperature (t-T) response curve. In vacuum the (t-T) curve on application of a step heat input shows exponential growth with one time constant while in air and He it shows significant departure from such a simple behavior. We could model the performance of the bolometer and have found that the departure from a single time constant arises because a finite mass of the gas ambient gets associated with the thermal response of the bolometer giving rise to an extra heat capacity and an associated thermal relaxation time. This changes the frequency response of the bolometer in presence of a cw sinusoidal signal input.

The bolometer used in this investigation consists of an array of 4 × 4 elements, each of which is a Si_3N_4 membrane (50μm × 50μm) grown on a Si wafer. A scanning electron microscope (SEM) image of a single element is
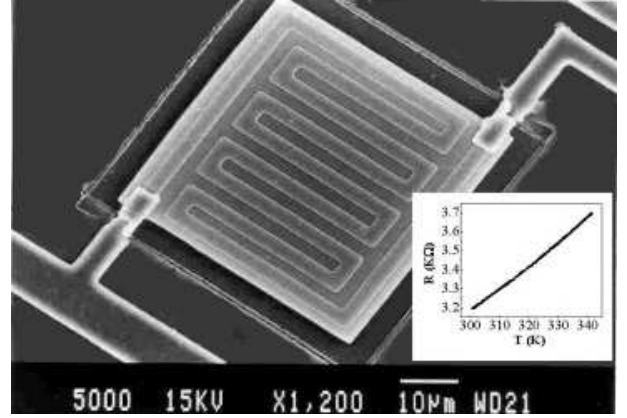

FIG. 1: SEM image of a single bolometer element. The inset shows the temperature dependence of the resistance of the Ti element.

shown in figure 1. The elements are connected to the main Si frame by Si_3N_4 hinges (5μm width x 2μm length x 1μm thickness). The thermal element is a Ti heater film $700\mathring{A}$ thick and 4μm wide.

The experiments were carried out in a chamber that can be pumped down to a vacuum of 10^{-5} torr. It can be filled with any desired gas upto a pressure of 1 atmosphere. The thermal characteristics were measured by giving a step power input to the bolometer thermal element (Ti) and recording the temperature response of the bolometer as a function of time which we call the (t-T) curve. For this we used the Ti element both as a heater and thermometer. To use the Ti element as the thermometer we calibrated the resistance of the Ti as a function of temperature using a standard Platinum thermometer in the temperature range 100K to 350K. The TCR = 1/R(dR/dT) $\sim 4\times10^{-3}$ /K. The observed calibration is shown in the inset of figure 1. The (t-T) curve was obtained by recording the voltage across the Ti element (which has a constant current bias) using a 16 bit A/D card at a rate of 10K points/sec. Step power input of amplitude P_{in} leads to a rise in temperature ΔT. In the steady state $\Delta T = P_{in} R_{th}$. To analyze whether the

*Electronic mail: ksnaga@physics.iisc.ernet.in
†Electronic mail: arup@physics.iisc.ernet.in, currently at S.N.Bose National Centre for Basic Sciences, Salt Lake, Kolkata 700098
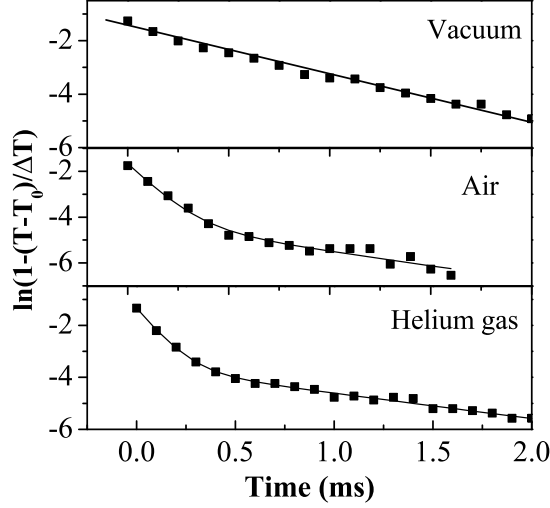
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FIG. 2: Thermal response curve of the microbolometers in vacuum, air and He gas. Lines show fits from the model. Note the single relaxation time behavior of the response in vacuum and two time constants dominated behavior in an ambient gas.

(t-T) is governed by one time constant or not we have plotted the quantity $ln(1 - (T(t) - T_0)/\Delta T)$ vs t where T_0 is the temperature of the bolometer in absence of the power input and is equal to the substrate temperature. When the (t-T) curve has a single time constant (τ) the $ln(1 - (T(t) - T_0)/\Delta T)$ vs t curve is a straight line whose inverse slope gives τ. Any departure from the single τ behavior will make this curve deviate from a straight line.

Typical examples of observed $ln(1 - (T(t) - T_0)/\Delta T)$ vs t curves are shown in figure 2 for vacuum and with Air and Helium ambience. In vacuum the thermal response can be characterized by a single τ, while in Air and He the curve can be described by a combination of two time constants. From the given P_{in} and the observed temperature rise ΔT, we could obtain R_{th} for all the experimental conditions- vacuum, Air and He ambience. The observed R_{th} is shown in figure 3 as function of temperature. In vacuum (pressure<10^{-3} mbar) $R_{th} \approx 2.5 \times 10^4 K/W$ at 300K and has a shallow temperature dependence. In vacuum, in absence of other thermal pathways, R_{th} will be determined by conduction through the hinges and the radiation contribution. Absence of a T^{-3} type of a steep temperature dependence in R_{th} shows that radiation makes a negligible contribution and R_{th} will be determined by the thermal conductivity Λ of the hinge material. From the hinge dimension and the observed R_{th} we calculate $\Lambda \sim 30 W/mK$ which is the same as the bulk value. In air and He there is a large reduction in R_{th} because the air and He ambience provides additional thermal link. Understandably, He which has higher thermal conductivity shows a lower R_{th}. Thus in gas environment it is the gas that determines the value
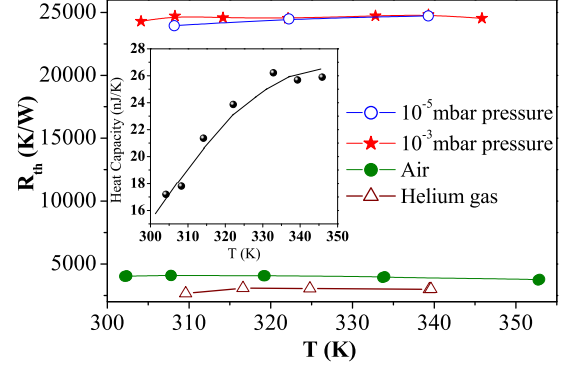

FIG. 3: The thermal resistance R_{th} in vacuum, air and He gas as measured from the steady temperature rise ΔT and P_{in}. The inset shows the heat capacity of the membrane as determined from our experiment.
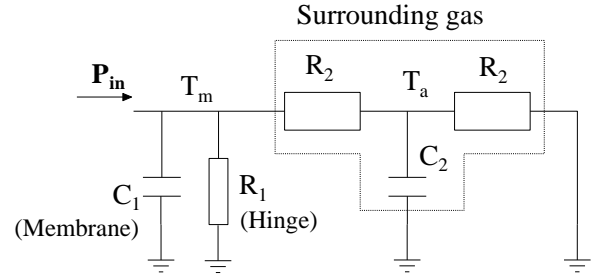

FIG. 4: A thermal model of the bolometer in presence of an ambient.

of R_{th} .

Next we analyze the observed thermal response curve shown in figure 2 using a simple model. The basic physics of the model is that the presence of an ambient gas not only provides a thermal link (thus changing R_{th}), but also provides a thermal mass, the heat diffusion through which has a finite time which will lead to additional time constants to the thermal response of the bolometer. The model is outlined below (see figure 4). To simplify we have used the approach of "lumped circuit" model where the thermal masses are represented as capacitors and the thermal resistances are shown as electrical resistors. This is less rigorous than the actual solution of the heat diffusion equation but it is simple to solve and it captures the essential physics.

In figure 4, T_m $(= T(t) - T_0)$ is the temperature of the membrane with respect to bath (substrate) temperature T_0. T_a is the average temperature of air with respect to the bath. R_1 is the thermal resistance of the hinge and C_1 is the heat capacity of the membrane and hinge combination. C_2 is the heat capacity of ambient gas that couples to the bolometer and R_2 is the thermal link due to the gas. We have taken the thermal links of gas to membrane

and gas to substrate both as R_2 for simplicity without sacrificing any feature. The heat balance equations are

$$P_{in}(t) = \frac{T_m - T_a}{R_2} + C_1 \frac{dT_m}{dt} + \frac{T_m}{R_1} \quad (1)$$

$$\frac{T_m - T_a}{R_2} = \frac{T_a}{R_2} + C_2 \frac{dT_a}{dt} \quad (2)$$

For a step heating $P_{in}(t) = 0$ for t < 0 and = P_{in} for t ≥ 0. The solution to this set of coupled differential equations gives:

$$T_m = P_1\{1 - exp(-gt)[P_2 exp(-ft) + P_3 exp(ft)]\} \quad (3)$$

where
$$2g = (\ (c^{-1} + 2\ )/\tau_2\ ) + 1/\tau_1$$
$$4f^2 = (1/c^2\tau_2^2) + (2/c\tau_1\tau_2) + (1/\tau_1 - 2/\tau_2)^2$$
$$P_1 = 2P_{in}/\ [C_1\tau_2(g^2 - f^2)]$$
$$P_2 = (1/2f)\ [\ (\tau_2(g^2 - f^2)/2) - (g - f)\ ]$$
$$P_3 = (1/2f)\ [\ (g + f) - \tau_2(g^2 - f^2)/2)\ ]$$

Here we have defined $\tau_1 = R_1 C_1$ and $\tau_2 = R_2 C_2$ and $c = C_1/C_2$. The model gives two time constants, $(g - f)^{-1}$ and $(g + f)^{-1}$. In vacuum, the thermal resistance $R_2 \rightarrow \infty$, $R_{th} = R_1$ and one gets the thermal response being controlled by one time constant τ_1. The fits to the data obtained using this model are shown in figure 2 as solid lines. In the case of the gas ambient the response curve with two time constants (eqn. 3) fits the observed data very nicely over the complete range of t over which data are taken. Typical τ_1 at T=300K is ≈ 0.5 sec. From the observed value of R_1 (obtained from the steady state value of ΔT and known value of P_{in}) we could find the heat capacity C_1 of the bolometer as a function of T for the temperature range studied (figure 3 inset). C_1 has the main contribution from the bulk of the heat capacity of the bolometer and approximately $1/3^{rd}$ the heat capacity of the hinges. Using this we get a specific heat of ≈ 1.95 J/gmK for the material of the bolometer and the hinge. This is much larger than the value of specific heat of ≈ 1 J/gmK for Si_3N_4. A value of ∼ 1.5J/gmK for the specific heat of Si_3N_4 has also been reported [4].

At steady state $t \rightarrow \infty$, $T_m = \Delta T = P_1$. From the observed fits of the data to equation 3, the time constants g^{-1}, f^{-1} and constants P_2 and P_3 can be found. Using the values of τ_1, R_1 and C_1 as observed in the case of the vacuum we can find out τ_2, R_2 and C_2, the parameters for the gas ambient. (In our model the parameters τ_1, R_1

and C_1 depend only on the membrane and hinge material and are independent of the ambient gas). The parameters τ_2, R_2 and C_2 are given in Table I.

The heat capacity C_2 is due to the extra thermal mass of gas around the bolometer through which the heat diffuses over the time scale of one to few τ_2. The volume of the gas calculated from the heat capacity is ∼ 1.34×10^{-10} m^3 for air and ∼ 2.34×10^{-10} m^3 for He. If the volume in which the heat diffuses is taken to be a hemisphere (since the cavity below the membrane ∼

TABLE I: Thermal parameters obtained from fits to the experimental data

Ambient	τ_1 (msec)	R_1 (K/W)	C_1 (nJ/K)	τ_2 (msec)	R_2 (K/W)	C_2 (nJ/K)
Vacuum	0.53	2.5×10^4	20	∞	∞	-
Air	0.53	2.5×10^4	20	0.37	4.0×10^3	155
Helium	0.53	2.5×10^4	20	0.40	3.1×10^3	222

$2\mu m$), its radius $(r_g) \approx 400\mu m$ for Air and $480\mu m$ for He. r_g thus should be comparable to the thermal diffusion length L_D of the gas. The L_D is estimated from the relation $L_D \approx \pi(\tau_2 D)^{0.5}$ where D is the diffusivity of the gas. From the standard $D = 5 \times 10^{-5} m^2 sec^{-1}$ for air $D = 1.1 \times 10^{-4} m^2 sec^{-1}$ for He we obtain $L_D \approx 440\mu m$ for Air and $\approx 650\mu m$ for He. It can be seen for both the gases $r_g \sim L_D$. This is a good validation of the essential physics used in the simple model. In a previous report it was shown that the R_{th} increases as the ambient is pumped and the vacuum is reached [4]. However, the issue of two relaxation times has not been addressed to. It may be appreciated that the deviation from a single relaxation time (τ) dominated thermal response as observed in an ambience of gas will severely change the often used expression for the responsivity, $R(\omega) \propto (R_{th}/\sqrt{1 + \omega^2\tau^2})$ which is strictly valid when the bolometer thermal response can be characterized by a single τ.

To summarize, in this paper we studied the effect of ambient gas on the thermal response of a microbolometer. We find that while in vacuum the thermal response can be characterized by a single time constant, the presence of ambient gas changes the nature of the thermal response and it needs two time constants to describe it. With a simple model we could connect the observed behavior to the physical parameters of the ambient gas.

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